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The use of laser radiation for endoscopic surgery has been a significant advance in patient care. The usual modality is to use an optical fiber to deliver the light energy from the laser to the patient. However, there have been a number of incidents of the optical fiber breaking while the beam was active. Although no injuries have been reported, we investigated the hazard posed by such broken fibers to operating room (OR) personnel. Optical fibers were fractured in a manner that simulated the fractures in the ORs and the output power and divergence measured. In most cases, the laser emission was still "beam -like", presenting a potential ocular hazard. Clearly proper use of eye protection and administrative controls are needed to avoid injuries.

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Can broken fiber optics produce hazardous laser beams?

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ABSTRACT

The use of laser radiation for endoscopic surgery has been a significant advance in patient care. The usual modality is to use an optical fiber to deliver the light energy from the laser to the patient. However, there have been a number of incidents of the optical fiber breaking while the beam was active. Although no injuries have been reported, we investigated the hazard posed by such broken fibers to operating room (OR) personnel. Optical fibers were fractured in a manner that simulated the fractures in the ORs and the output power and divergence measured. In most cases, the laser emission was still "beam-like", presenting a potential ocular hazard. Clearly proper use of eye protection and administrative controls are needed to avoid injuries.

1. INTRODUCTION

One of the more popular surgical lasers is the Laserscope KTP/532 Surgical Laser System. This system employs a quasi-CW Nd:YAG laser that can be operated at the fundamental wavelength of 1064 nm or at the second harmonic of 532 nm by the use of a potassium titanyl phosphate (KTP) crystal. The ability to use different wavelengths that may be either preferentially absorbed by different tissue or give different effects such as photocoagulation and cauterization increases the flexibility of the system[1,2]. This class 4 laser is designed to deliver the optical energy via a optical fiber inside of an endoscope to the surgical site inside the body. The endoscope also has a viewing fiber so that the surgeon can observe the tissue site. Different size fibers are used with the system ranging from 200 to 600 microns in diameter. The system can deliver a significant amount of power through the fibers, up to 60 W at 1064 nm and 20 W at 532 nm. When operated in the IR, a helium-neon laser operating at 632.8 nm is used as an alignment beam. An attenuated 532 nm beam is used for alignment when operating at the 532 nm wavelength.

The purpose of this paper is to assess the potential ocular hazard that may be present when the optical fiber is broken. Infrequently, some users of the KTP/532 system have inadvertently broken the fiber while the laser was in use.[3,4] Typical scenarios are someone stepping on the fiber in a darkened operating room while the attention is focused on the surgical procedure underway or the fiber fracturing where it enters the endoscope and flexes at too great an angle. In many cases, laser eye protection is not worn by all the OR personnel because the output end of the fiber is expected to be inside of the patient prior to full power being delivered. Clearly, intentionally operating the laser with the end of the fiber outside of the patient ("freespace lasing") poses a significant hazard that can be avoided by proper control procedures. It is the sudden fracture of the fiber while the laser is still being operated by the surgeon that is of concern here. The initial laser hazard potential

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was evaluated by the Radiation Services Branch of the Armstrong Laboratory.[5] They recommended that quantitative measurements be made on the broken fibers to determine if the optical radiation from the broken end could pose an ocular hazard. To resolve the concerns of broken fibers in the OR, the Laserscope KTP/532 Surgical Laser System was tested at the Armstrong Laboratory's Laser Branch. This report will summarize these measurements. The Laser Branch has played an active role in testing numerous laser systems and providing laser safety consultation to governmental agencies or companies involved in the development and testing of the laser systems.

2. LASER HAZARD ANALYSIS

For the determination of appropriate maximum exposure limits (MPEs) and laser Nominal Hazard Zones (NHZs), the following laser characteristics must be known:[6]

a. wavelength
b. exposure duration
c. output spatial profile
d. output temporal profile
e. output power
f. beam divergence
g. operating limits including operator adjustments, output limits, and environmental conditions

The wavelength (λ) was either 1064 nm or 532 nm, depending on the mode of operation. The system incorporates a 25 kHz Q-switch; however, the temporal fluctuations in power about the nominal value were measured and found to be sufficiently small so that the power could be assumed to be a constant. For laser safety considerations, the exposure duration used in determining the MPE is taken to be 0.25 sec for the 532 nm beam based on the aversion response to bright light. (Of course, a longer exposure could be used if appropriate.) The Maximum Permissible Exposure (MPE) for a 0.25 s exposure in the visible is 2.55×10^{-3} W/cm^2 for a CW laser. This MPE is used to calculate the Nominal Ocular Hazard Distance (r_{NOHD}) from the fiber tip and the Optical Density (OD) of laser eye protection. The maximum system power output is 20 W at 532 nm and 60 W at 1064 nm. In a typical endoscopic procedure, using 18 W of 532 nm through a 600 micron fiber the r_{NOHD} and OD are as follows (see the appendix for details of hazard calculations):

r_{NOHD} = 1.83 meters

OD @ 532 nm = 4.3

One can readily see that a broken fiber would certainly presents a potential hazard if the output is "beam-like".

3. FIBER OUTPUT MEASUREMENTS

The output power was measured with both a Scientech Model 3600 power/energy meter and a Photodyne 66XLA power meter using a Model 350 head. These measurements were compared to the internal power meter on the Laserscope KTP/532.

The spatial beam profile was measured with a Cohu 4810 CCD camera coupled to a personal computer running the Beamcode 6.1 software from Big Sky Software. The CCD camera set-up is shown in Figure 1. This configuration gave consistent results for a wide range of powers. The software gave a variety of data including power, beam

diameter, beam profile, gaussian fit (for TEM_{00} modes) and beam divergence. The power was first measured using a power meter and this value was input into Beamcode so that the computer power calculations gave absolute values.

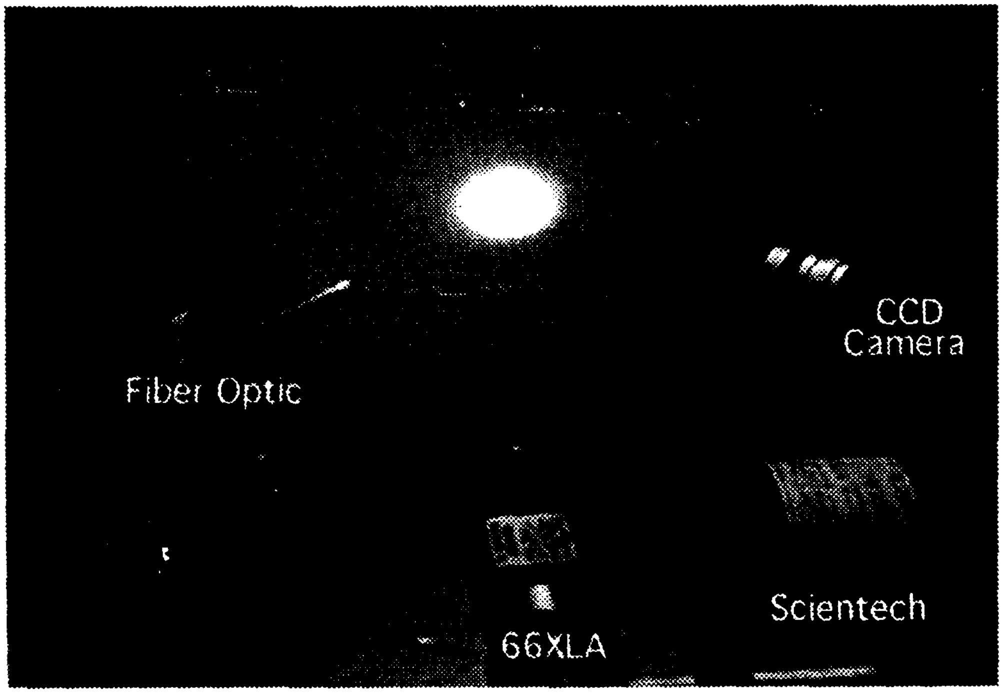

Fig. 1. Fiber optic measurement set-up.

3.1. Measurements of 600 micron fiber at 532 nm

The 600 micron fiber was used for a study of the hazards of a broken fiber. We chose the setting of 0.5 W on the KTP/532 as an operating power because it permitted long exposures with the diagnostics and relatively safe operation. Power meter measurements using the Scientech indicated 0.42 W of power actually being delivered at the output of the fiber.

Our first series of measurements were done on an unbroken fiber. Seven samples were taken by the beamcode software and the results analyzed. The average power was 0.418 W. The average divergence was 48.3 mrad. The spatial profile was very close to gaussian profile. The 3-D profile is shown in Figure 2; slice plots through the peak are shown in Figure 3. The slices fit a gaussian with a correlation of 0.97. These results are typical of the high quality, stable beam that we measured with new fibers at different output powers.

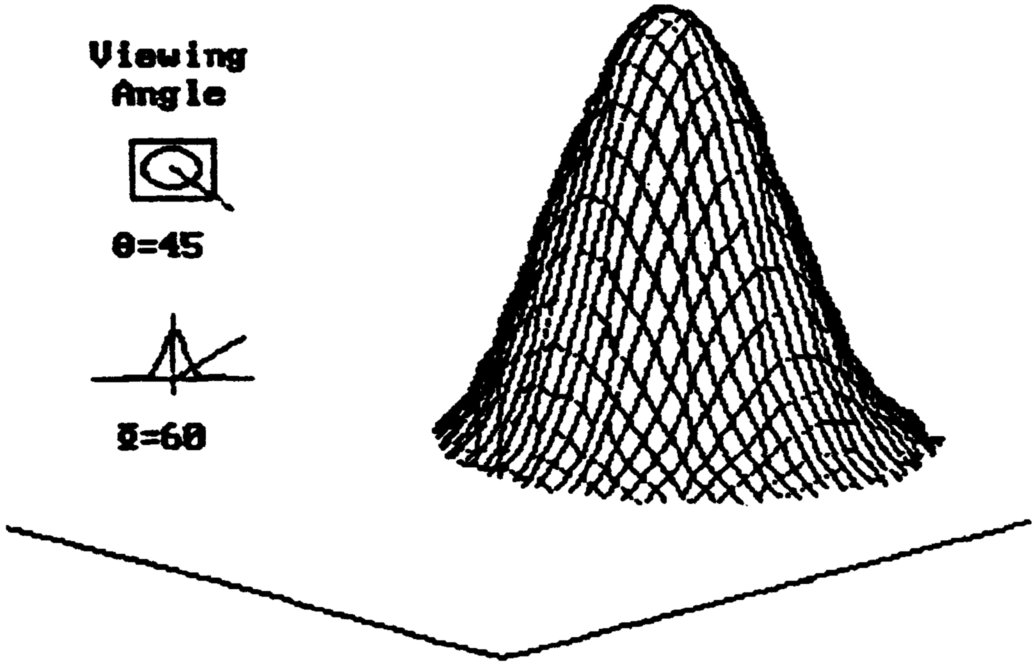

Fig. 2. Normal 3-D profile of 532 nm beam through 600 micron fiber.

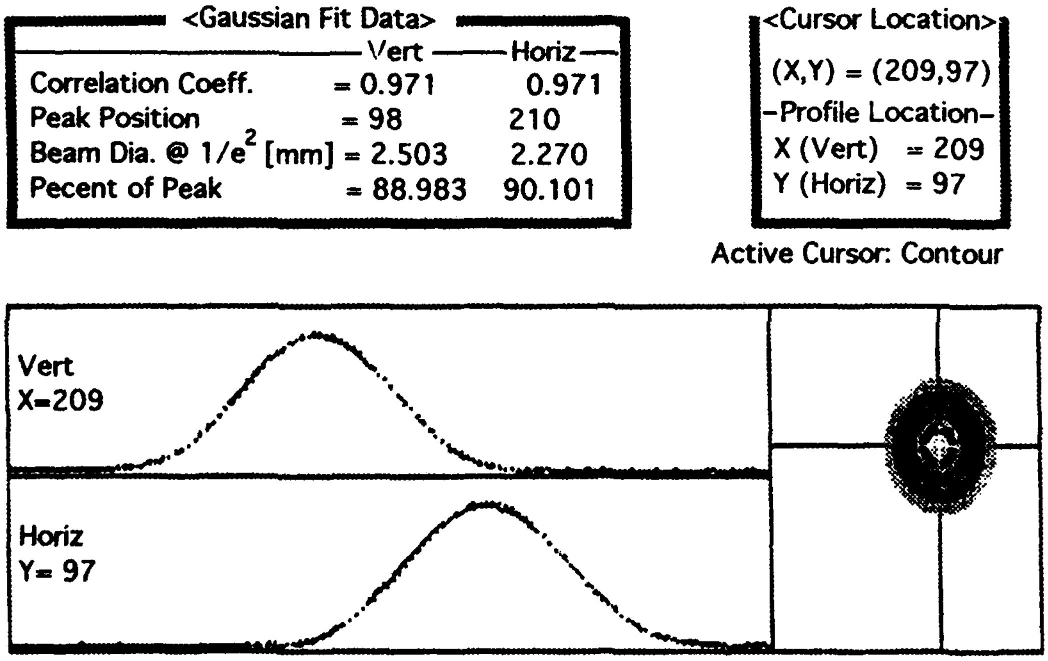

Fig. 3. Gaussian correlation profiles of fig. 2.

We then broke a number of fibers. It should be noted that the fibers were not easily broken. However, if the fiber was pushed against a hard edge such as the edge of a table, a fracture could be obtained. This simulated the reported fractures. We did not quantify the amount of pressure needed to break the fiber. Examination of the fractured ends usually revealed a angular break, (Fig. 4). We expected the output from the broken fibers to be mostly diffuse; however, we found that these broken fibers would usually still produce a beam-like output that went off at some angle to the fiber axis. A good example is shown in Figure 5 where a broken fiber produced two output beams, the smaller beam propagating along the fiber axis and the more distorted beam propagating at about 90 degrees from the fiber axis. In this case, the camera was viewing both the end of the fiber and the scattered beam. For this particular case, the laser was set at 0.5 W and we measured 0.13 W coming directly out the end of the fiber. The sidelobe contained about the same amount of power, as shown in Figure 5. With a normal 532 nm operating power of 18 W, the sidelobe in this case would have contained as much as 5 W producing a 0.25-second NOHD of almost one meter.

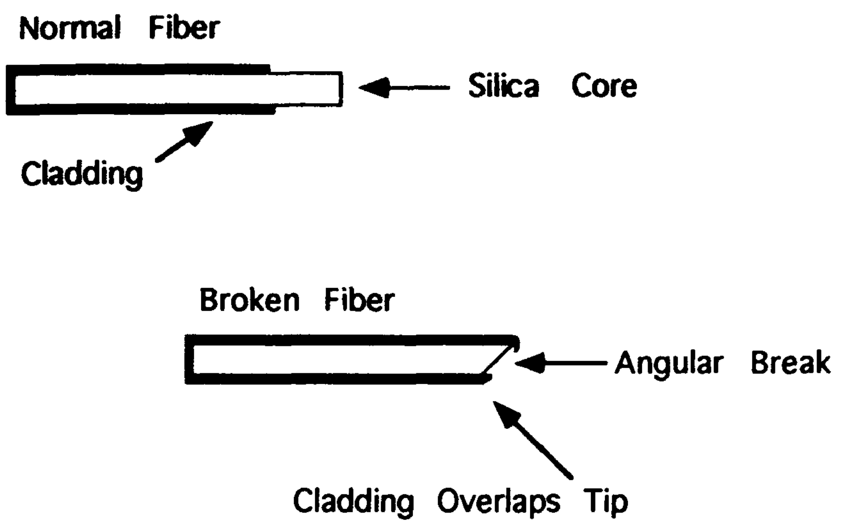

Fig. 4. Normal and broken fiber optic tips.

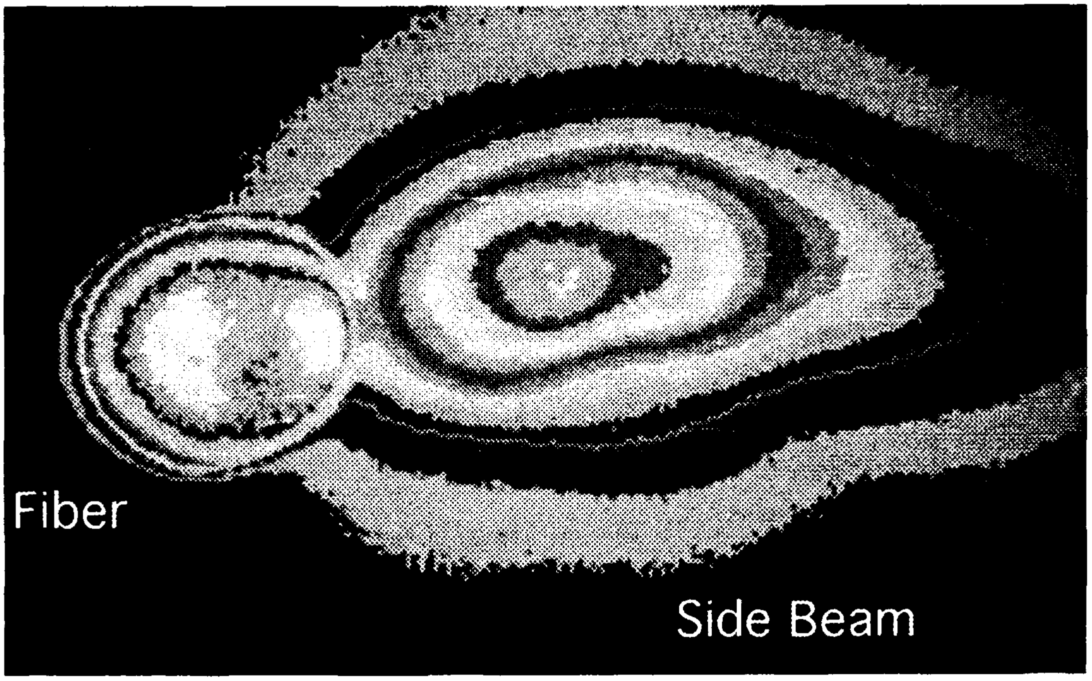

Fig. 5. Main and 90 degree 532 nm beams from broken fiber.

3.2. Infrared beam measurements

We also examined the output from an unbroken 600 micron fiber when the laser was operating at 1064 nm. The output beam had excellent spatial profile as shown in Figure 6. The laser was set to operate at 5 W; the measured power was 4.6 W using the Scientech power meter and averaged 4.57 W using the CCD camera and the Beamcode software.

3.3 Laser eyewear evaluation

Laserscope provided Uvex laser protective eyewear with the KTP/532 system. This eyewear had the optical density spectral scan as shown in Figure 7. One can see that the provided eyewear was more than adequate for the various fibers configurations with inadvertent viewing of the laser beam.

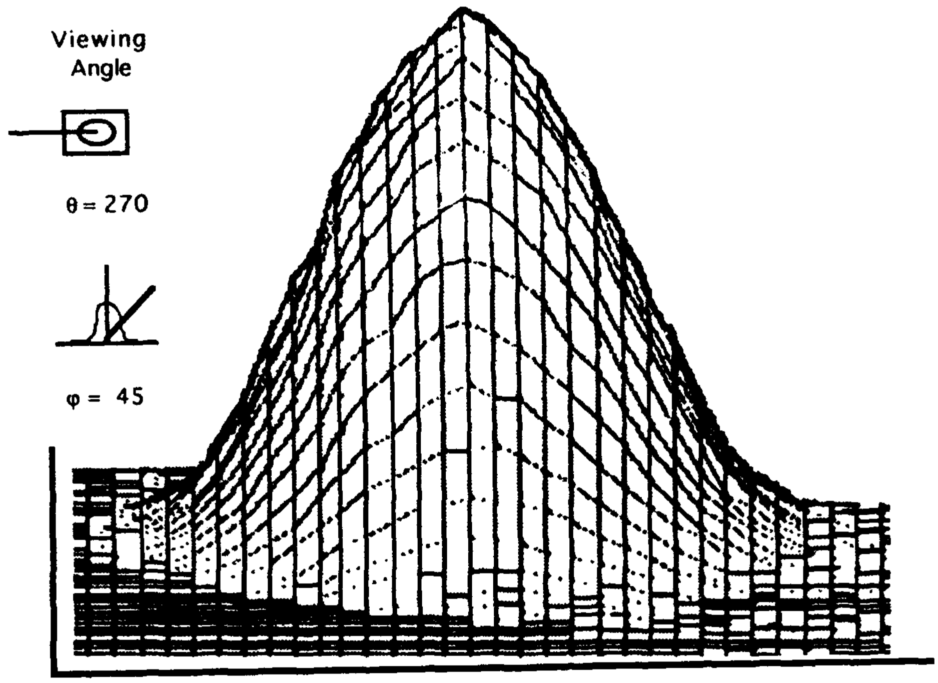

Fig. 6. Normal 3-D profile of 1064 nm beam through 600 micron fiber.

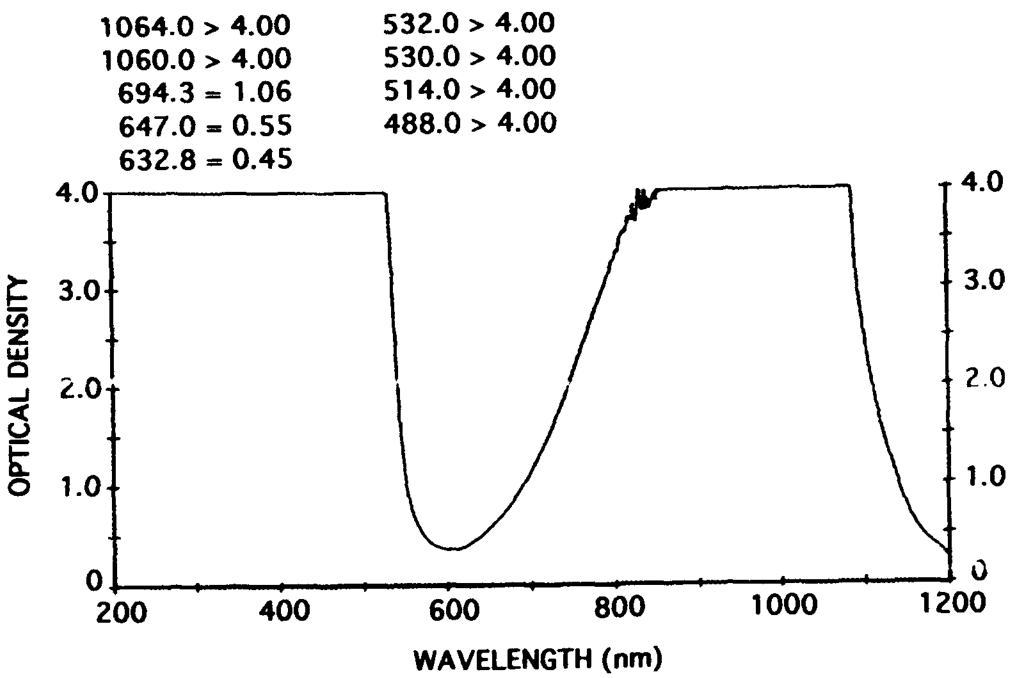

Fig. 7. Spectral optical density of KTP/532 laser protective eyewear.

4. DISCUSSION

The laser system has a very well designed procedure for getting an output beam. There is a safety interlock that prevents an output beam unless a fiber is connected to the system. The fibers are packaged in a sterile wrapping and are designed for a single use only. Sterilizing and re-using the fiber is not recommended. The fibers come cleaved and polished on the output end. A tool is available to cleave the fiber if necessary. Beam profile measurements were taken with polished fibers as well as fibers we cleaved in the laboratory. In both cases, the beams appeared to be nearly gaussian TEM_{00} in spatial profile.

The beam-like nature and the amount of output power from the broken fiber indicate that the broken fiber can pose an ocular hazard. Although the probability of an eye exposure from this beam is quite small, the use of laser eye protection by all OR personnel is the correct and prudent control procedure for this system.

In a number of cases, the fibers that were broken did not severe the plastic sheath that surrounds the fiber. We observed a bright spot at the fracture site when the laser was operating at 532 nm. The output was not an ocular hazard but we postulated that the sheath might be burned by the optical beam and cause a fire hazard. However, in the test series using 0.5 W, we did not observe any burn-throughs of the fibers. We adjusted the power up to 10 W without seeing any effect. Higher power settings may be needed to observe this effect.

Engineers at Laserscope have proposed an interesting solution. If the fiber is broken, laser light is emitted into the room. The Laserscope personnel have developed a box with several wide field-of-view photodetectors to measure the emission and, if detected, shut off the laser. The device looks for the characteristic modulation of the quasi-CW output beam. This internal control has great promise and needs further investigation. In particular, it could substantially decrease the maximum exposure time, lessening the hazard of the output from a broken fiber or a fiber that is inadvertently operated in free space. Whether such an add-on device could be a sufficient control procedure so that laser eye protection would be unnecessary is not clear with the information we have at this time.

We also examined several other configurations with the laser system. We found that the 200 micron fiber gave exceptionally good beam profiles with powers accurately displayed on the KTP/532. This fiber could only be connected to one of two output ports of the laser. When changing fibers in the other port, we also encountered some problems with some of the 400 and 600 micron fibers charring at the input end, resulting in negligible power exiting the fiber despite a normal reading from the internal power meter. Discussions with the Laserscope engineers suggest that this problem was due to misalignments within the system. Such potential problems lead us to recommend that the alignment and operation of the KTP/532 laser be checked on a regular basis by a technician at the hospital where the device is being used and that the laser be test-run if it is moved from room to room.

Finally, personnel involved with the installation, operation, maintenance, and service of Health Care Laser Systems (HCLS) must consult the American National Standard for the Use of Lasers in Health Care Facilities.[9] This standard has the requisite engineering, procedural, and administrative controls necessary for the safety of patients and health care professionals.

5. CONCLUSIONS

The laser light emitted by broken fibers could present an eye hazard. Thus the conservative recommendation is that laser eye protection be worn by all OR personnel when the laser is being operated. Further, good control procedures should be used by the nurse who is operating the laser to observe the fiber for possible fractures. However, the safety risk is minimal because (1) it is difficult to break the fibers, (2) the plastic sheath did not separate or burn through in our tests, and (3) the output, though still beam-like is rapidly diverging. The laser needs good alignment prior to use, consistent with the training given by Laserscope when the system is delivered.

Additionally, a fire hazard may also exist if the laser beam is absorbed by other material such as surgical drapes. In the oxygen-rich atmosphere of an operating room (OR), such a fire could be disastrous.

Overall, the laser is a well designed, highly flexible system for a variety of surgical applications, but the laser needs good alignment prior to use.

Recommended OR procedures:

-- precalibration by technician with optical power meter.
-- eyewear should be worn by all OR personnel.
-- extra care must be taken to protect the fiber.
-- the fibers should only be used once.
-- possible modification to KTP/532 to shut down if fiber is broken.

Above all, proper calibration of surgical lasers is as important for the medical laser and health care service personnel as the calibration of ionizing radiation sources.

6. ACKNOWLEDGMENTS

The authors wish to thank Laserscope for the use of the KTP/532 system used in the measurements and for their genuine concern for producing a safe laser product. In particular, we thank Debbie Lohmeyer, John J. Stulak, Rush Goodson, and Mike Harris of Laserscope Inc. for their personal help.

7. APPENDIX

a = Beam diameter of laser beam at exit aperture (1/e) intensity points.
A = Area of laser beam at exit aperture.
A_r = Area of laser beam at range (r).
D_L = Diameter of laser beam at range (r).
r_{NOHD} = Distance from laser output where irradiance (E) (W/cm^2) of laser beam is equal to the Maximum Permissible Exposure (MPE).
E_p = Irradiance (W/cm^2) of CW laser beam incident on eye protection.
NA = Numerical aperture of fiber
OD = $D\lambda$ = Optical Density of eye protection.

Range equation for multi-mode fiber optics (r_{NOHD}):

$$r_{NOHD} = \frac{1.7}{NA} \left\{ \frac{\Phi}{\pi \bullet MPE} \right\}^{1/2} \quad (1)$$

The above is shown for CW lasers; where Φ is in (Watts) and the MPE is in (W/cm^2). Now to calculate the hazardous viewing distance for momentary viewing (0.25second). We need to find the visible laser 0.25 s MPE from Table 5 in Z136.1.[8]

For t = 0.25 s, $MPE = 1.8\ t^{3/4} \times 10^{-3}\ J/cm^2 = 1.8\ (0.25)^{3/4} \times 10^{-3}\ J/cm^2$

$MPE_H = 6.36 \times 10^{-4}\ J/cm^2$ (MPE in radiant exposure - for pulsed lasers)

$MPE_E = MPE_H/t$ (MPE in irradiance = MPE_H/exposure time) (2)

$MPE_F = (6.36 \times 10^{-4}\ J/cm^2)/0.25\ s = 2.55 \times 10^{-3}\ W/cm^2$

NOW:

$$r_{NOHD} = \frac{1.7}{0.44} \left[\frac{18\ W}{\pi \bullet 2.55 \times 10^{-3}} \right]^{1/2}$$

$r_{NOHD} = 1.83 \times 10^2$ cm = 1.83 meters

Now for optical density (OD) of laser eye protection:

$OD = D\lambda = \log_{10}(E_p/MPE)$ (3)

$E = \Phi/A_r$ = (Output power)/(Effective area) (4)

Since the fiber diameter is smaller than the visible limiting aperture of 7 mm, the effective area is equal to the area of the limiting aperture for optical density determinations. See ANSI Z136.1-1986, paragraph 4.6.2.5.1.[6]

$E = (18\ W)/0.385\ cm^2 = 46.75\ W/cm^2$

$D\lambda = \log_{10}(46.75\ W/cm^2/2.55 \times 10^{-3}\ W/cm^2) = 4.3$ OD

The 400 and 200 micron fibers have numerical apertures of 0.30 and 0.22 respectively. The r_{NOHD} for these two fibers at 532 nm would be:

$$r_{NOHD} = \frac{1.7}{0.30} \left[\frac{18\ W}{\pi \bullet 2.55 \times 10^{-3}} \right]^{1/2} = 2.69 \text{ meters}$$

$$r_{NOHD} = \frac{1.7}{0.22} \left[\frac{18\ W}{\pi \bullet 2.55 \times 10^{-3}} \right]^{1/2} = 3.66 \text{ meters}$$

The required optical density at 532 nm would remain as 4.3 OD.

The Laserscope KTP532 can operate in the 1064 nm mode up to 60 Watts. Normally, one would not use an inadvertent exposure of 0.25 s for the invisible 1064 nm

wavelength, but there is visible HeNe beam coaxial with the 1064 nm beam. We could then, use a 0.25 s exposure for the 1064 nm beam in this case.

From Table 5 of ANSI Z136.1-1986, the 0.25 s MPE for 1064 nm is:

For $t = 0.25$ s, $MPE = 9\ t^{3/4} \times 10^{-3}\ J/cm^2 = 9\ (0.25)^{3/4} \times 10^{-3}\ J/cm^2$

$MPE_H = 3.18 \times 10^{-3}\ J/cm^2$ (MPE in radiant exposure - for pulsed lasers)

$MPE_E = MPE_H/t$ (MPE in irradiance = MPE_H/exposure time)

$MPE_E = (3.18 \times 10^{-3}\ J/cm^2)/0.25\ s = 1.27 \times 10^{-2}\ W/cm^2$

Using the same numerical apertures for the 600, 400, and 200 micron fibers as above, we can now determine the 1064 nm r_{NOHD}s.

$$r_{NOHD} = \frac{1.7}{0.44}\left[\frac{60\ W}{\pi \bullet 1.27x10^{-2}}\right]^{1/2} = 1.5 \text{ meters}$$

$$r_{NOHD} = \frac{1.7}{0.30}\left[\frac{60\ W}{\pi \bullet 1.27x10^{-2}}\right]^{1/2} = 2.2 \text{ meters}$$

$$r_{NOHD} = \frac{1.7}{0.22}\left[\frac{60\ W}{\pi \bullet 1.27x10^{-2}}\right]^{1/2} = 3.0 \text{ meters}$$

The laser eye protection optical density required at 1064 nm would be:

$E = (60\ W)/0.385\ cm^2 = 155.8\ W/cm^2$

$D\lambda = \log_{10}\ (155.8\ W/cm^2/1.27 \times 10^{-2}\ W/cm^2) = 4.1$ OD

Since the eye is less sensitive to damage at 1064 nm than at 532 nm, the more powerful 60 W, 1064 nm beam poses about the same hazard as the 18 W, 532 nm beam.

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